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# POROSITY AND PERMEABILITY DEVELOPMENT IN THE OLIGOCENE-MIOCENE BLUFF FORMATION, GRAND CAYMAN

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## ABSTRACT

Present day porosity and permeability in the Bluff Formation of Grand Cayman is a result of numerous constructive and destructive processes. Porosity was created by (1) preferential dissolution of aragonite fossils, (2) solution widening of joints and fissures, (3) development of solution caverns and passages, (4) tree root borings, (5) microborings, and (6) selective dissolution of the cores of dolomite rhombs. The high permeability is related to extensive network of joints which transect the island and the well developed karst system. Porosity and permeability destruction occurred through the (1) deposition of caymanite, grainstones and terra rossa, and (2) precipitation of speleothemic calcite and carbonate cements.

The creation and destruction of the porosity in the Bluff Formation was controlled by the interplay of climatic conditions and the successive cycles of regressions and transgressions that have affected Grand Cayman over the last 30 million years. During some regressions porosity was created because the carbonates were dissolved during influx of fresh water. At other times, however, conditions were suitable for the formation of speleothemic calcite, calcite and dolomite cements and/or terra rossa and this led to porosity reduction. The onset of transgressive conditions led to porosity destruction because marine sediments were commonly brought onshore and flushed into the cavities via the well developed joint and cave systems.

The combination of constructive and destructive processes has produced a heterogeneous aquifer of which the hydraulic information is difficult to interpret. The integration of hydrogeological data, hydrochemical information and the geological evolution of the island has led to an improved understanding of the manner in which the ground water behaves because water-rock interactions affects the hydrogeological properties of the aquifer and hence, the ground water flow. Such information is invaluable in the development and management of this valuable resource.

## INTRODUCTION

An effective prediction of porosity and permeability distribution in the Oligocene-Miocene Bluff Formation (Fig. 1) is essential to the management of ground water resources on Grand Cayman. Conversely, chemical characteristics of the present-day ground water can be used to examine the conditions for the formation of diagenetic fabrics present in the rocks. The present day porosity and permeability distribution in the Bluff Formation is a result of the numerous constructive and destructive processes which produced heterogeneous aquifers. Interpretation of the porosity and permeability distribution in the dolostones of the Bluff Formation, therefore, requires a detailed study of the mechanisms involved in porosity creation and destruction. These mechanisms are controlled by extrinsic (climate, vegetation, and time) and intrinsic (lithology, structure, and stratigraphy) factors.

This study (1) identifies the porosity styles and evaluates their conditions of development, (2) identifies the cavity fills and evaluate the conditions for their formation, (3) highlights the relationship between porosity distribution and ground water flow regime, and (4) emphasizes the effect of sea level fluctuations on diagenetic modification of the Bluff Formation. This study is based on hydrological and hydrogeological data collected over a three year period from 1985 to 1988. The petrographic signatures of the rocks were determined from some 160 thin sections.

## GEOLOGICAL FRAMEWORK

Grand Cayman (Fig. 1A) is formed of the Oligocene-Miocene Bluff Formation and Pleistocene Ironshore Formation (Fig. 1B; Matley, 1926; Vaughan, 1926; Brunt et al., 1973; Rigby and Roberts, 1976; Jones et al., 1984; Jones and Hunter, 1989). A disconformity divides the Bluff Formation into the early late Oligocene Cayman Member and the middle Miocene Pedro Castle Member (Jones and Hunter, 1989). The lithology of the Bluff Formation is typically a dense, white to light tan, finely crystalline dolostone. The Pleistocene Ironshore Formation, which unconformably overlies the Bluff Formation, is formed of limestone (Brunt et al., 1973; Jones et al., 1984).

## HYDROLOGICAL REGIME

The fresh ground waters are recharged by infiltration of precipitation not lost to evapotranspiration or surface runoff. The patchy soil cover together with the intense jointing and karsting (Folk et al., 1973; Rigby and Roberts, 1976; Jones and Smith, 1988) suggest that the Bluff Formation should have a high infiltration capacity. Rapid recharge, recorded by water table hydrograph of well 7-84EE following each rainfall (Figs. 1B, 2), probably occurs when rain water infiltrates through the fissures or caverns. The rapid decline of the water table demonstrates the efficient transmission of the ground water in the aquifer (Fig. 2).

Recharge is also indicated by the improvement of water quality recorded by piezometer 4-84LV (Figs. 1B, 3). The rain water probably causes dilution of water salinity in the shallow aquifer during rapid recharge. The sharp decrease in salinity at the end of May, 1986 (Fig. 3) was in response to a storm that lasted for 12 days with a total rainfall of 246 mm.

A significant part of the precipitation generally is lost through evapotranspiration. On Grand Cayman, where the temperature averages about 28°C, evapotranspiration is an active process. Evapotranspiration also has a significant impact on the chemical quality of the ground water. The fluctuation of water salinity with time recorded by piezometer 4-84LV (Fig. 3) is caused by the interplay between the rain water recharge and evapotranspiration.

## HYDROGEOLOGICAL REGIME

Fresh water accumulations on Grand Cayman (Mather, 1972) are typically lens shaped and entirely land locked (Fig. 1B); features that are common on small limestone oceanic islands (Mather and Buckley, 1973; Vacher, 1978; Lloyd, 1980; Ayers and Vacher, 1986). The major fresh water lenses on Grand Cayman are developed in an unconfined condition in the Bluff Formation (Fig. 4A), where the land surface elevations are highest.

Fresh water lenses developed on Grand Cayman typically have an irregular configuration (Fig. 4A) that is controlled by the attitude and orientation of the joints and fissures. Commonly, the lens thickness is not in agreement with the general theories of the Ghyben-Herzberg principle (Fig. 4B) as developed by Herzberg (1901). This is probably because of the continual changes in the ground water compositions, the mixing effect of the fresh and underlying saline water, and the heterogeneity and anisotropy of the aquifers.

The highly permeable nature of the karstic bedrocks prevents the development of surface streams. Thick soil cover is also

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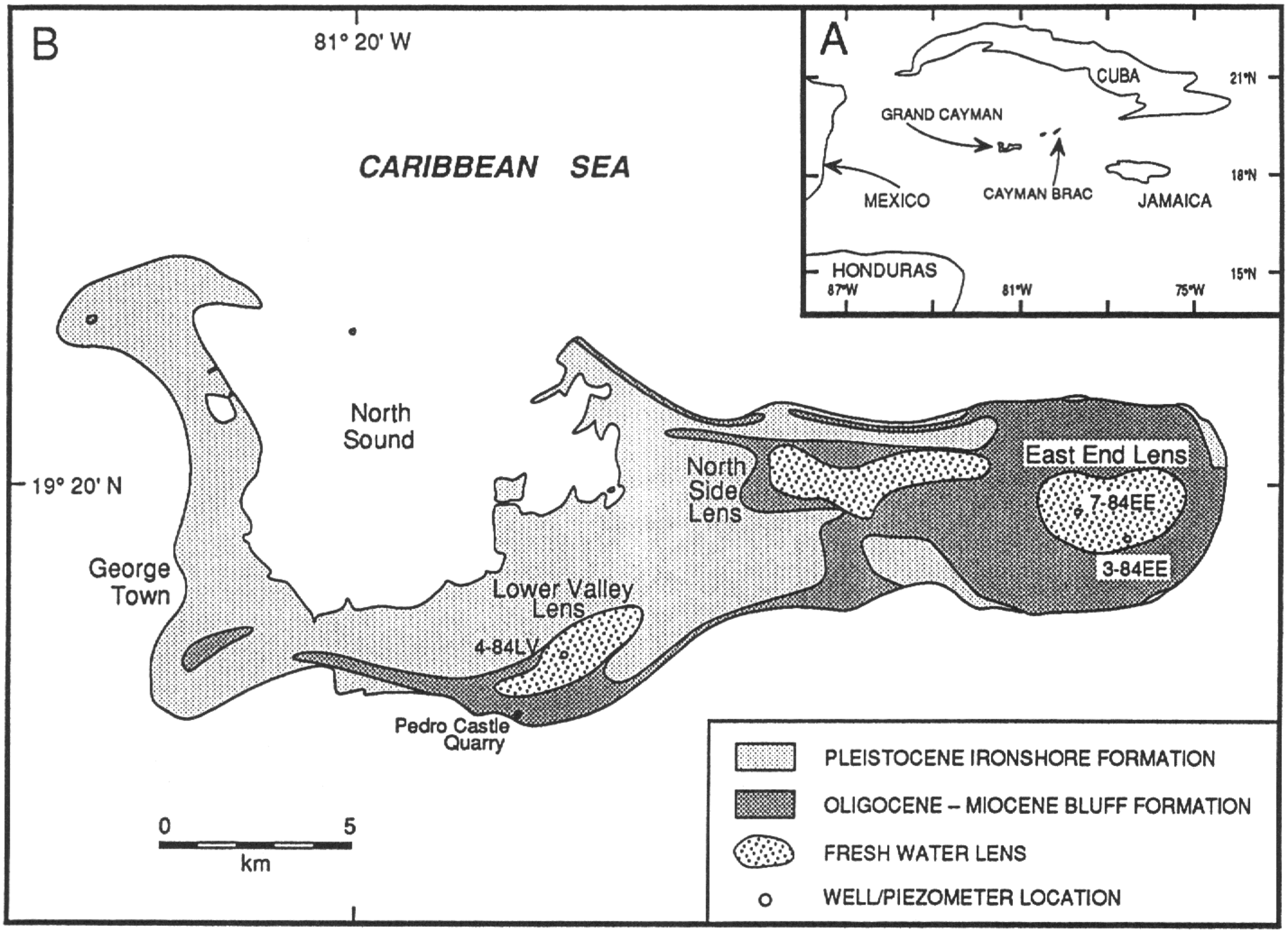


Fig. 1. (A) Geographic location of the Cayman Islands. (B) Hydrogeological setting of the fresh ground water occurrences on Grand Cayman and location of wells and piezometers cited in text.

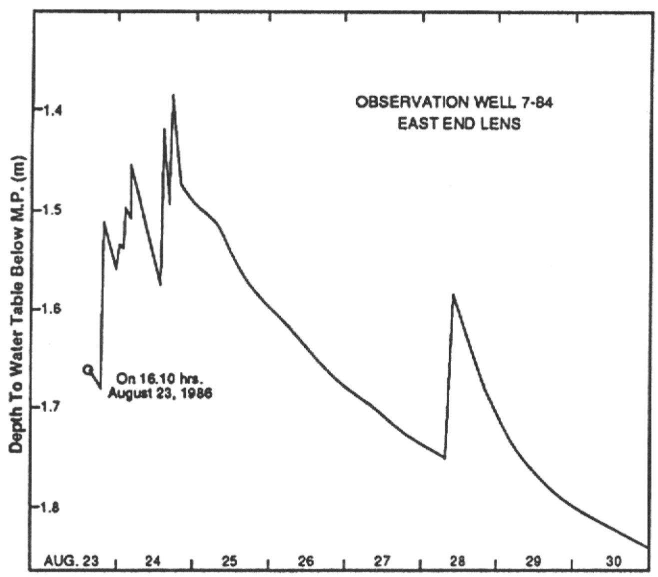


Fig. 2. Water table hydrograph of well 7-84EE showing rapid infiltration and discharge of rain water in response to rainfall events. M.P. is measuring point at top of the well casing.

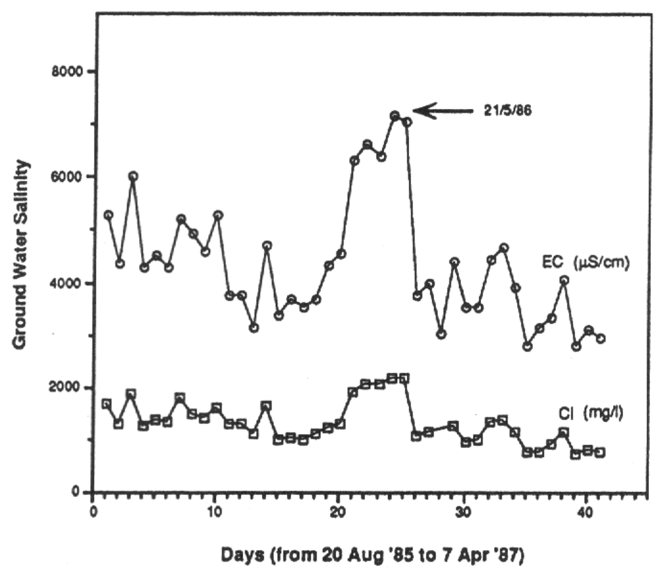


Fig. 3. Temporal variation of ground water salinity in the Lower Valley lens recorded by piezometer 4-84LV in stalled in the lightly brackish water zone.

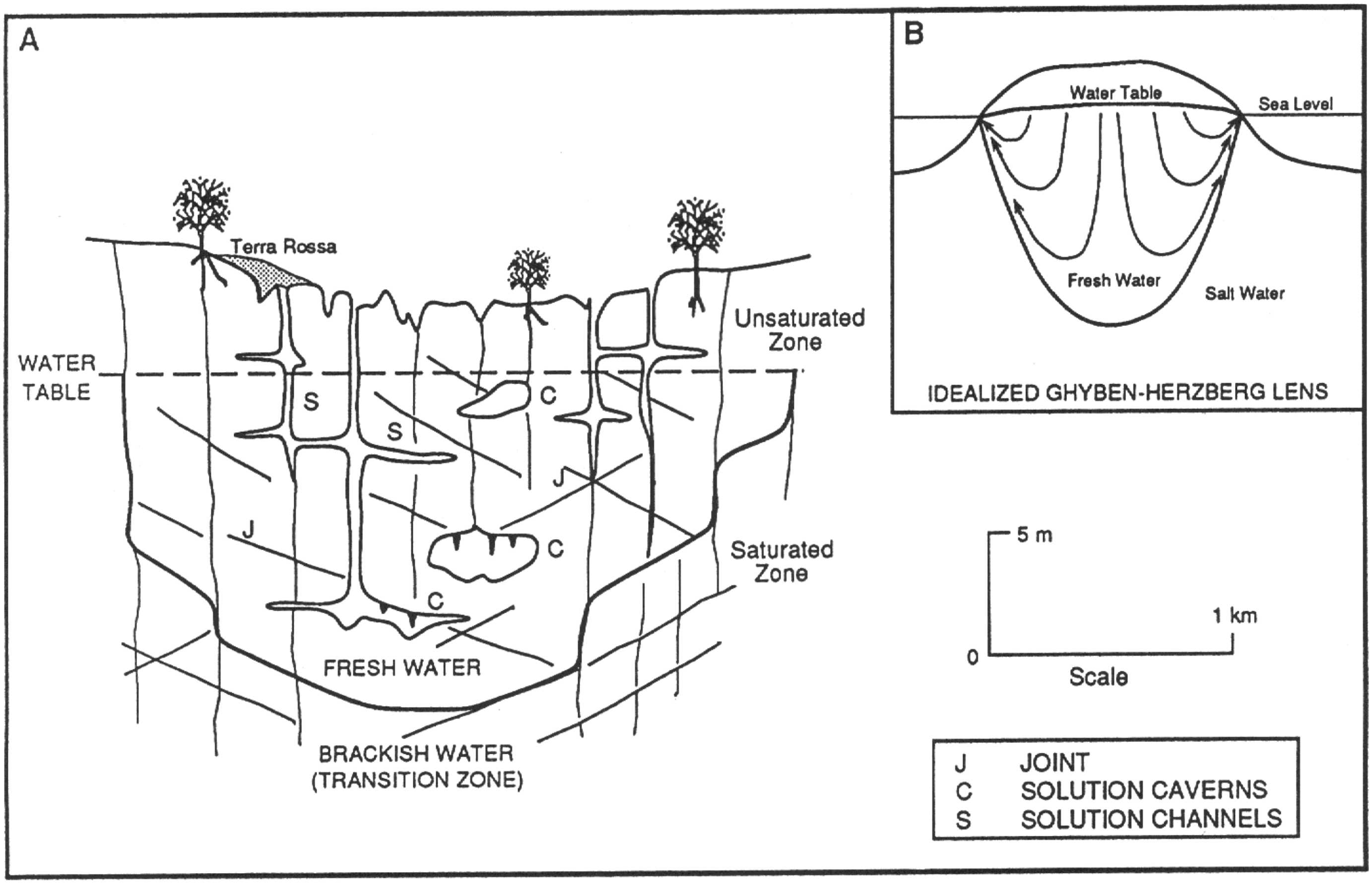


Fig. 4. (A) Schematic representation of joint and karst controlled lens configuration on Grand Cayman. (B) Idealized Ghyben-Herzberg lens.

absent because of the high infiltration rate of rain water. The high transmissivity of the aquifer, which results in limited storage of fresh water in the aquifer, is well exemplified by the low ground water table elevations (Fig. 5).

The sea around Grand Cayman generally experiences an average semi-diurnal tide range of 0.2 m and a seasonal fluctuation

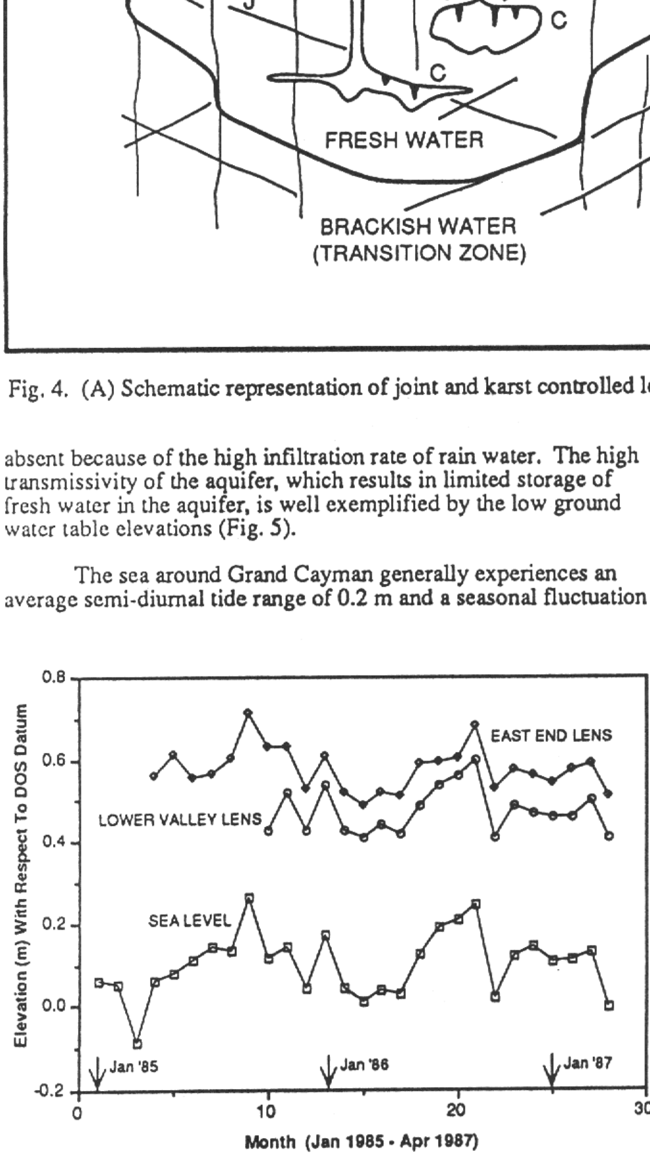


Fig. 5. Average monthly sea level around Grand Cayman and water table elevation of Lower Valley and East End Lens. DOS refers to Directorate Overseas Survey datum.

of about 0.4 m (Fig. 5). The ground water table fluctuates in response to the sea tides (Fig. 5) because the aquifers are hydraulically linked to the surrounding ocean. As a result, a thick transition zone of brackish water develops between the fresh and sea water (Fig. 4A) in response to tide generated hydrodynamic dispersion. A similar phenomenon occurs in the Bahamas (Mather and Buckley, 1973), Bermuda (Vacher, 1978), Enewetak (Wheatcraft and Buddemeier, 1981), and Majuro Atoll (Anthony et al., 1989).

## POROSITY STYLE

Dolostones of the Bluff Formation have variable porosity owing to the diversity of pore types. Most primary intergranular porosity was obliterated through pervasive dolomitization (Jones et al., 1984; Pleydell, 1987). Primary intergranular porosity does, however, occur in a rubble facies (rhodolite rudstone) on Cayman Brac and, locally, in skeletal grainstone which is composed of fragments of red algae and foraminifera. Most porosity was created by (1) preferential leaching of metastable carbonates prior to dolomitization, (2) jointing and fracturing, and (3) karsting. Tree root borings and microborings can be important in creating porosity in the surface and near-surface zones. Locally, secondary intracrystalline porosity formed by selective dissolution of the unstable zones of dolomite are common.

### Skeletal Moldic Porosity

Preferential dissolution of original skeletal aragonite in the molluscs, gastropods, and corals was common in the Bluff Formation (Folk et al., 1973; Jones et al., 1984; Jones and Hunter, 1989). Conversely, skeletal components formed of high-magnesian calcite, such as red algae and most foraminifera, have been dolomitized and their textures preserved. Locally, up to 25% moldic porosity occurs in the dolostones.

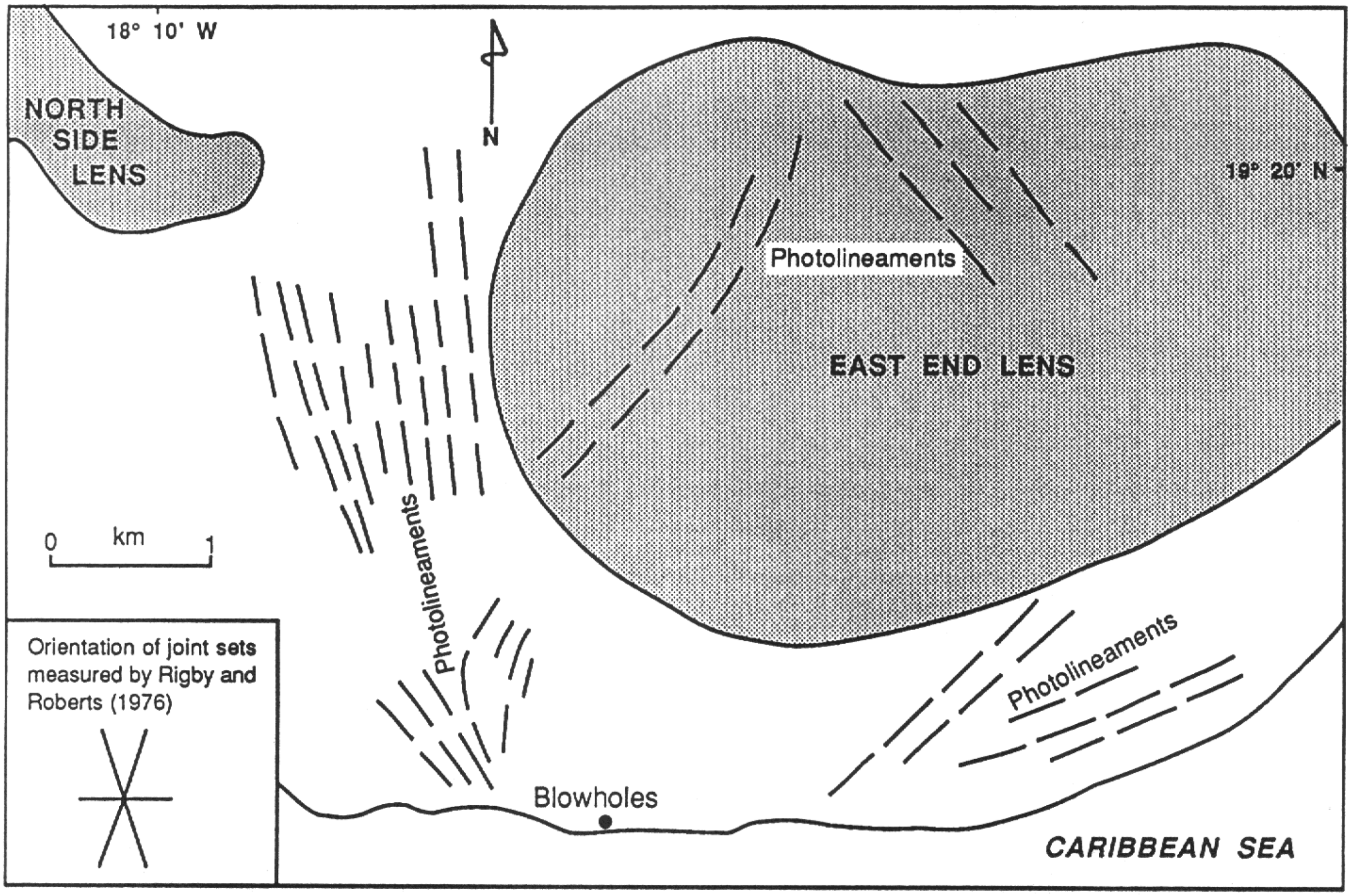


Fig. 6. Structural photolineaments near the East End lens on Grand Cayman. Inset shows joint directions determined by Rigby and Roberts (1976).

### Fissures and Joints

Detailed joint measurement on the coastal exposures of the Bluff Formation on Grand Cayman showed three major joint sets trending at about 20°, 90° and 160° (Rigby and Roberts, 1976). Structural photolineaments, which are surface expressions of subsurface joints and fissures, are particularly pronounced on the eastern half of Grand Cayman where the Bluff Formation is exposed. Near the East End lens (Fig. 1B), two vertical conjugate photolineaments striking 030-040° and 175° (Fig. 6) are particularly well developed. Southward to the coast, besides the east-west trending joint set, two joint groups trending 050° and 160° are present (Fig. 6). Around the Lower Valley lens (Fig. 1B), dominant photolineaments, commonly indicated by the alignment of small ponds, trend at 020° and 150°.

### Karst Porosity

Cave systems, preferentially developed along joints and at water table zones, are common in the dolostone of the Bluff Formation. At depth, extensive networks of solution passages and chambers (Fig. 4A) are commonly indicated by the sudden drop of drilling tools and the lack of cutting returns.

### Root Moldic Porosity

Plant (trees, bushes and grasses) commonly root directly into the dolostones of the Bluff Formation and penetrate the rocks either through existing joints or by chemically excavating the substrate as they grow. Porosity in the upper 3 m can be as high as 50% due to the actions of plant roots.

### Microborings

Microborings (generally <10 μm diameter), formed by the action of algae, fungi and bacteria are common in the surface zones of the Bluff Formation (Folk et al., 1973; Viles and Spencer, 1983; Jones, 1989). The density of microborings tends to be high around the tree roots because many of the micro-organisms are symbiotically associated with the plant root systems.

### Hollow Dolomite Rhombs

Locally, the dolomite rhombs in the Bluff Formation have had their cores removed by selective dissolution (Jones et al., 1989). Such dissolution typically occurs in dolostones on weathered surfaces or joint surfaces.

## CONDITIONS FOR POROSITY CREATION

Selective dissolution of the aragonitic skeletal materials reflects the thermodynamical instability of aragonite under earth surface conditions (Bathurst, 1975; Berner, 1981). Subaerial exposure of metastable carbonate sediments of the Bluff Formation undoubtedly occurred during the relative sea level drops in late Oligocene and late Miocene times.

Studies of Pleistocene limestones led Land (1970), Steinen and Matthews (1973), and Pingitore (1976) to conclude that dissolution of biogenic aragonite is more effective in the fresh water phreatic environment than in the vadose setting. It is possible, therefore, that dissolution of aragonitic skeletal components in the Bluff Formation may have occurred in a similar setting.

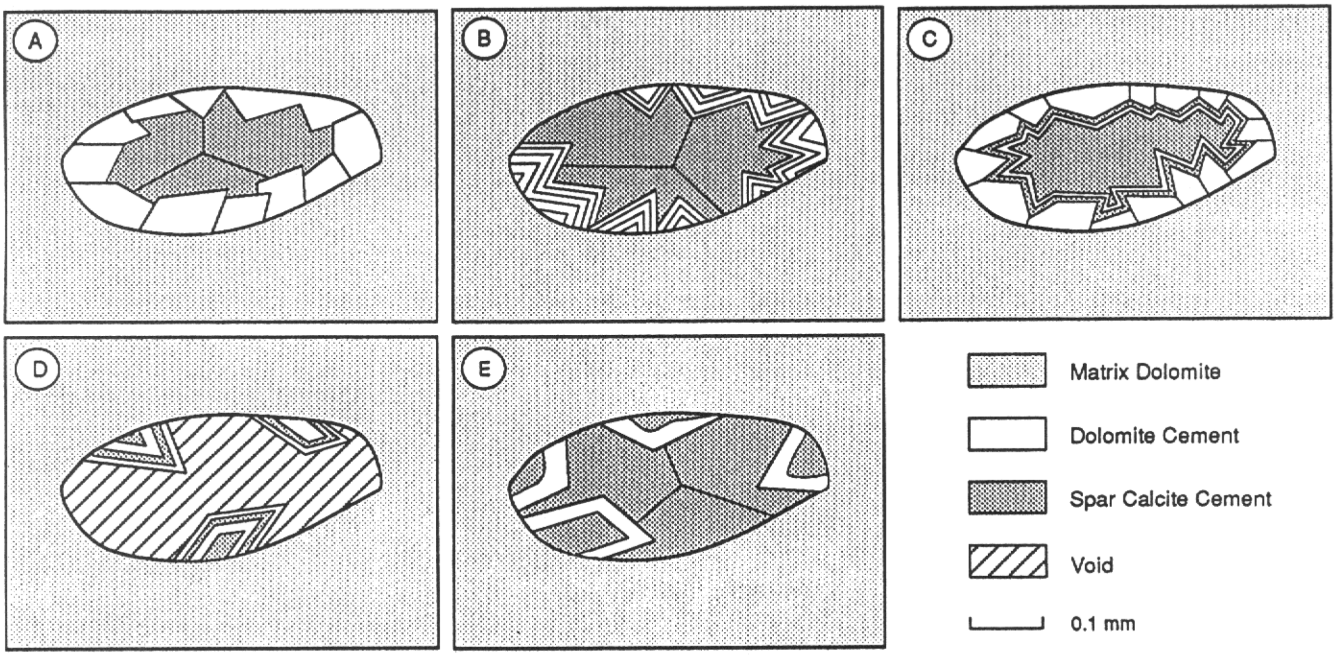


Fig. 7. Schematic diagram showing cement types in the Bluff Formation. (A) Clear euhedral dolomite and sparry calcite. (B) Zoned euhedral dolomite and sparry calcite. (C) Alternating bands of dolomite and calcite. (D) Intracrystalline zoning of dolomite and calcite. (E) Poikilotopic calcite-dolomite.

Joints and fissures are important in porosity creation because they provide avenues for fluid movement. Uniformity and intensity of the joint sets present in the Bluff Formation (Fig. 6) and the fact that the Cayman Islands are sited on the Cayman Ridge (Uchupi, 1975; MacDonald and Holcombe, 1978) suggest that the joints are probably related to past tectonism of the Cayman Trench. Differential enlargement of fissures by solution resulted in concentrated flow, which increased dissolution rates and further enlarged the incipient caverns and channels. This dissolution phenomenon leads to the development of permeable zones in the aquifer system.

On the Cayman Islands, there is clear evidence that caves were developed both pre- and post-dolomitization of the host rocks (Jones and Smith, 1988). Therefore, karsting in the Bluff Formation is a multiple phase phenomenon. The fact that the largest caves on Grand Cayman and Cayman Brac formed after dolomitization of the Bluff Formation suggests that climatic conditions, and density and openness of joints probably were more dominant in controlling the extent of karsting than lithology.

Biological control has been largely ignored by many workers in evaluating porosity distribution in carbonates. Extensive dissolution of spar calcite mediated by fungi was experimentally demonstrated by Jones and Pemberton (1987a, 1987b). More importantly, Jones and Pemberton (1987a) suggested that under the mediation of fungi, dissolution of calcite occurs via surface reaction controlled kinetic processes without the intervention of vast quantities of fluid. Besides being a source of $CO_2$ through root respiration, root borings also provide avenues for water flow.

Where ground water is in continual motion through pores, it dissolves and carries away soluble material, which in turn increases ground water circulation and the permeability in the rock. The zone of greatest permeability tends to develop in the zone of greatest circulation, which is commonly just below the water table (Thrailkill, 1968; Stringfield and Rapp, 1977; Esteban and Klappa, 1983; LeGrand, 1983). Rapid rain water recharge through open fractures can also cause significant undersaturation at the water table zone by introducing water of low salinity. Furthermore, the shallow water zone is most likely to receive $CO_2$ from the respiration of plant roots and organic decay.

In the brackish water transition zone which develops between fresh and sea water, Runnells (1969), Hanshaw et al. (1971), Badiozamani (1973), and Plummer (1975) suggested that undersaturation with respect to calcite occurs as a result of mixing. Stoessell et al. (1989) showed that aragonite is preferentially dissolving throughout the modern mixing zone along the Caribbean coast of the Yucatan Peninsula. Furthermore, Sanford and Konikow (1989) suggested that significant porosity development occurs when a large influx of fresh water occurs in the aquifers.

Jones and Smith (1988) suggested that mixing corrosion, which occurs in the mixing zone, was probably responsible for the development of most caves on Grand Cayman. A similar mechanism was proposed for the karst features formed on the Bahamas (Palmer, 1984; Mylroie, 1984) and the Yucatan Peninsula (Hanshaw and Back, 1980; Back et al., 1986). Ford (1988), however, argued that such mixing is physically infeasible unless the rock mass has very high effective porosity. Furthermore, on small islands like Grand Cayman, mixing corrosion is less effective because of the absence of large hinterland for fresh water recharge.

At the ground water discharge zone, permeability increases as a result of concentrated flow (Chidley and Lloyd, 1977; Lloyd, 1980). On Grand Cayman, there is no geological boundary in defining the base of the mixing zone; therefore, porosity enhancement is probably most favourable near the coast at the discharge zone where flow rate is high. Indeed, cave development on Grand Cayman tends to be locally extensive along the coast. Paleoclimatic conditions are equally important. The karsting and speleothemic deposits on Grand Cayman suggest that they did not develop under present day climatic regime, but probably developed in the past when the rainfall was much higher. Therefore, karstification on the Bluff Formation is predominantly controlled by sea level elevation and climatic conditions. Cave geometry is controlled by jointing and ground water flow regime.

## CAVITY FILLS

Secondary pores, irrespective of their origin, were commonly filled or partly filled by multi-phase carbonate cements, flowstone, and internal sediments (Fig. 7; Jones et al., 1984; Jones and Smith, 1988).

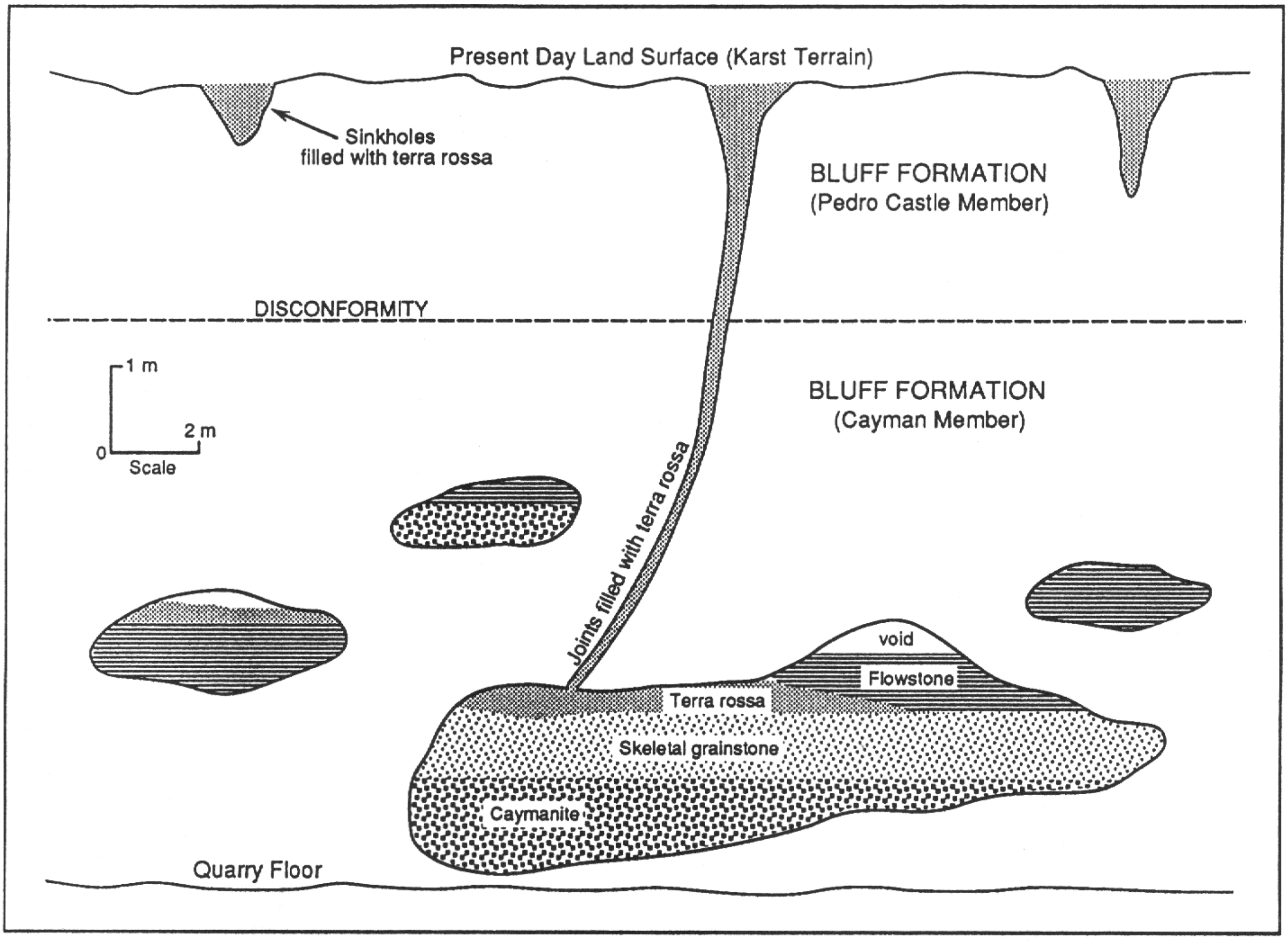


Fig. 8. Schematic diagram of quarry wall exposure at Pedro Castle Quarry (Fig. 1B) showing cave fills in the Cayman Member of the Bluff Formation.

### Carbonate Precipitates

Euhedral, clear or zoned dolomite typically developed as the first phase of cement lining cavities (Figs. 7A, 7B). At least two generations of dolomite cement occur in some cavities. The first generation of dolomite cement precipitated prior to internal sedimentation whereas the second generation of dolomite cement formed on top of the internal sediments.

Precipitation of sparry calcite cements, which followed the dolomite cements, commonly occluded the cavities (Figs. 7A, 7B). This dolomite-calcite couplet, previously documented by Jones et al. (1984) in the Bluff Formation, also occurs in other dolomitic limestone sequences (e.g. Land, 1973; Kaldi and Gilman).

Alternating zones of dolomite and calcite occur in two forms. The first type of alternating zones (10 µm thick) that are laterally continuous from crystal to crystal (Fig. 7C). The second type of alternating zones occurs in a single crystal (Fig. 7D).

Poikilotopic calcite that encases dolomite cement and matrix dolomite produced fabrics (Jones et al., 1989) comparable to those considered indicative of dedolomite (e.g. Shearman et al., 1961; Evamy, 1967). The poikilotopic calcite-dolomite commonly associated with the zoned dolomite-calcite cements (Fig. 7E).

Flowstone commonly filled cavities, joints and caverns in the Bluff Formation (Fig. 8; Lockhart, 1986; Jones and Smith, 1988). Some caves are decorated with various forms of speleothems (Jones and Motyka, 1987; Jones and Smith, 1988; Jones and MacDonald, 1989).

### Internal Sediments

Caymanite, formed of tightly interlocking anhedral microcrystalline dolomite, is a common cavity and cave fill in the Bluff Formation (Fig. 8). It is characterized by (1) white, orange/red and black colour bands, (2) geopetal texture, (3) cross bedding, and (4) cut and fill channels. Rare examples also contain foraminifera and gastropods. Dolomitized skeletal grainstone is commonly associated with caymanite (Fig. 8). The skeletal components are predominantly red algae and foraminifera.

Terra rossa in the Bluff Formation is formed of organic rich glaebules embedded in microcrystalline carbonate and clay matrix. However, it is not clear if the terra rossa is of residual or foreign origin. Terra rossa breccia, which has dolostone fragments embedded in the soil, is common in some cavities and open joints.

## CONDITIONS FOR POROSITY DESTRUCTION

### Carbonate Precipitation

Speciation calculations for ground waters from Grand Cayman indicate that almost all the fresh to saline waters are supersaturated with respect to calcite. Thus, according to thermodynamic

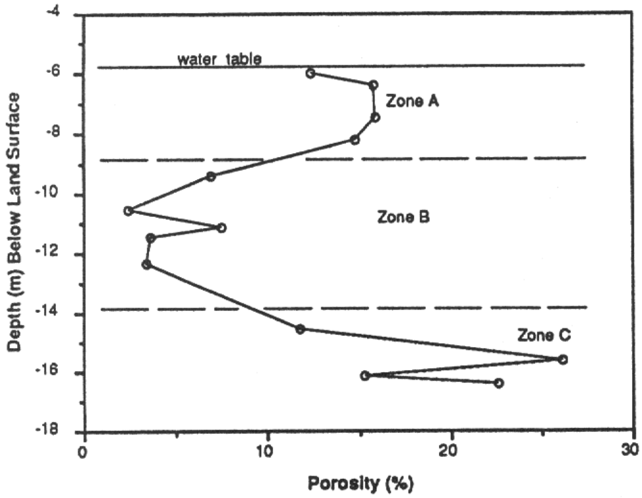


Fig. 9. Porosity distribution with depth shown by analysis of rock cores from well 3-84EE.

considerations, calcite precipitation should be common throughout all hydrochemical zones. Folk and Land (1975) suggested that sparry calcite precipitation occurs in meteoric waters or dilute subsurface waters with Mg/Ca ratios from 1:1 to 1:10. The common occurrence of calcite cement in present day fresh water zone also suggests that precipitation of sparry calcite probably occurs in water of low salinity.

Most waters from the dolostone aquifer of the Bluff Formation are supersaturated with respect to dolomite. Therefore, theoretically, the ground waters are also capable of precipitating dolomite. Dolomite cements may form in mixing zones (Folk and Land, 1975; Land 1985; Machel and Mountjoy, 1986; Hardie, 1987). The decrease in the content of dolomite cement as the last cement phase from the slightly brackish to saline water zones in the Bluff Formation also suggests that dolomite cement in the Bluff Formation probably formed in the brackish water zone.

The alternating growth of dolomite and calcite cement probably represents periods of ionic depletion followed by subsequent ionic replenishment of the pore solutions. During cement growth in the cavities, the degree of supersaturation of the pore solutions with respect to the precipitating mineral decreases. This decrease in ionic concentration may lead to the formation of another mineral variety or complete cessation of cement growth.

Dissolution of unstable dolomite zones in zoned dolomite crystals probably occurred during periodic influxes of $CO_2$-charged rain water, which is most effective at the water table zone or along joints. Furthermore, rain water recharge would have caused undersaturation of the ground water with respect to dolomite at the water table zone. Shallow ground waters on Grand Cayman are commonly supersaturated with respect to calcite and have a relatively low Mg/Ca ratio, which are most favourable for precipitating calcite that filled the leached zones and remaining cavity.

The precipitation of speleothemic calcite is typically regarded as an abiogenic process (e.g. White, 1976; Kendall and Broughton, 1978). Studies on Cayman speleothems by Jones and Motyka (1987) and Jones and MacDonald (1989), however, demonstrated that formation of speleothems may, to some extent, be biogenically controlled.

### Internal Sedimentation

The presence of normal marine skeletal components (foraminifera and red algae) in the grainstone led Jones and Hunter (1989) to suggest that the skeletal sands were deposited during the early part of a marine transgression. The origin of caymanite, however, is less certain. Folk and McBride (1976) and Lockhart (1986) suggested that caymanite was formed from materials washed from swamps into the cavities and caverns via the well-developed joint system during seasonal storms. The presence of terra rossa at various stratigraphic levels suggests that the soils probably entered the cavities and caverns via the well developed joint and karst systems in a manner similar to the transport of caymanite (Fig. 8).

The multiple cycles of caymanite formation is best illustrated by the distinct laminations and cut and filled channels. The presence of (1) erosional features and cross-bedding, (2) large angular fragments, and (3) fragments probably removed from irregular projections on cavity walls suggests that sedimentation occurred under high-stage flow conditions.

The variation in grain size of sediments in the same layer indicates that the sediments were transported in steady turbulent flow in a manner suggested by Bridge (1981). Gales (1984) also suggested that finer sediment can be deposited simultaneously with the coarser sediment where flow expansion resulted in a sudden reduction in flow competence, such as at the exit to the phreatic zone. A similar mode of flow and transport was probably responsible for the caymanite sedimentation in the Bluff Formation. Cross-bedding in the caymanite further indicates high fluid flow regime during its deposition.

## POROSITY DISTRIBUTION AND FLOW REGIME

Porosity distribution in cores from well 3-84EE (Fig. 1B) indicates three distinct porosity zones, herein termed A, B and C (Fig. 9). An examination of the rock cores shows that the porosity in zone A developed near the water table zone probably resulted from active ground water circulation at the water table. Active dissolution due to mixing corrosion and high hydraulic erosion is a characteristic of the shallow phreatic zone (Thrailkill,1968; Stringfield and Rapp, 1977; Esteban and Klappa,1983). The differences in porosity between zones B and C (Fig. 9) appears to be facies control. Zone C has a high content of leached corals whereas zone B has only scattered, leached mollusc fragments. This vertical variability of porosity in the Bluff Formation shows that ground water flow in the aquifer system is heterogeneous even over a short distance.

Parizek (1976), LaRiccia and Rauch (1977) and LeGrand (1979) demonstrated that wells penetrating fractures generally have high flow rates. On Grand Cayman, the joints, fissures, caverns and solution channels probably affected the ground water flow regime by: (i) providing a direct hydraulic connection between the aquifer and the surrounding ocean (Fig. 5), (ii) creating semi-confined conditions in an unconfined aquifer (Fig. 4A), (iii) providing avenues for mixing of water from different hydrochemical zones, (iv) allowing rapid recharge of rain water into the aquifer (Fig. 2), (v) defining the lens geometry as shown by the irregular lens geometry and sharp lens boundary (Figs. 1B, 4A), (vi) being responsible for the intrusion of the saline water which divides and prevents linkage of the North Side and East End lenses (Fig. 6), and (vii) facilitating leaching process by providing pathways for fluid flow.

## RECORDS OF SEA LEVEL FLUCTUATIONS

In order to unravel the diagenetic history of the Bluff Formation, it is imperative to reconstruct the paleohydrogeology which controlled the diagenetic regime. Past tectonic activity caused differential uplift or down faulting of the Cayman Islands prior to the late Pleistocene (Stoddart, 1980; Woodroffe, 1988), and resulted in the development of joints and fissures (Rigby and Roberts, 1976).

For the Tertiary period, the most significant sea level fall of nearly 400 m took place in the late Oligocene (Vail et al., 1977). Olsson et al. (1980), however, argued that a rapid sea level drop of up to 150 m occurred in the early Oligocene. The major regression near the end of the Miocene is well documented (Adams et al., 1977; Vail et al., 1977; Loutit and Keigwin, 1982; Haq et al., 1987). Jones and Hunter (1989) suggested that the stratigraphic record in the Bluff Formation is in agreement with the global pattern of sea level changes as postulated by Vail et al. (1977) and Haq et al. (1987). Thus, according to Jones and Hunter (1989), the Cayman Member of the Bluff Formation was subaerially exposed in late Oligocene and early Miocene times. Subsequent to transgression in Miocene times led to the deposition of the Pedro Castle Member. The entire sequence was exposed in late Miocene as a result of the late Miocene regression (Jones and Hunter, 1989).

Although the records of Pleistocene sea level fluctuation on the Cayman Islands are less complete than those on Barbados (e.g. Mesolella et al., 1969; Bender et al., 1973), there are several lines of evidence to suggest that the islands were subjected to fluctuating sea levels during the Quaternary. They include: (i) well defined wave cut notches on the north coast of Grand Cayman and around Cayman Bac (Fig. 1A) at about 6 m above present sea level (Woodroffe et al., 1983), which probably developed at the time when the Ironshore Formation (125,000 years old) was being deposited (Jones and Smith, 1988); (ii) wave-cut notch at about 2.5 m above present sea level on the southeastern coast of Grand Cayman (Woodroffe et al., 1983); (iii) two levels of caves along the cliff face on Cayman Brac (Fig. 1A) at about 18 m and 30 m above present sea level, probably related to past sea levels as suggested by their horizontal orientation; (iv) submerged wave cut notches around Grand Cayman at about 19 m below present sea level and possibly at about 150 m below present sea level (reported by pilots of the research submersible submarine); and (v) low marine terraces (six levels at 2 m, 4 m, 6 m, 8 m, 11 m and 15 m) above present sea level (Emery, 1981) and submerged terraces around Grand Cayman (Rigby and Roberts, 1976).

## DISCUSSION

Available evidence suggests that the Bluff Formation has been subjected to more than one cycle of subaerial exposure since late Oligocene times because of sea level fluctuations. Precise dating of the different stages of karstification is difficult, because each stage of karst development further modified the inherited karst features. Stringfield et al. (1979) noted that in areas where paleokarst is not too deeply buried, it may be incorporated into the present circulation system such as the artesian aquifer of Tertiary age in southeastern Georgia and Florida. Thus, the present day hydrogeological regime on Grand Cayman is the end product of numerous past and present processes. It is also difficult to assess the depth of karstification in response to each sea level change because of the overlapping karst effect. Furthermore, changes in the surface and ground water drainage began as soon as the carbonate rocks were elevated above sea level and circulation was established.

In addition to the effect of past sea level high stands, the extensive networks of cave systems are probably related to solution features preferentially developed along joints and fractures in a manner suggested by Ford and Ewers (1978) and Ford (1988). Jointing on Grand Cayman is a multi-phase phenomenon and is one of the pre-requisite parameters for cave formation by providing avenues for fluid flow, and hence, carbonate dissolution. Joints of different attitudes near Blowholes (Fig. 6) contain diverse fills which are similar to those filling caves in the Cayman Member of the Bluff Formation (Fig. 8). This relationship suggests that jointing and karsting are closely related to one another. The karsting and speleothemic deposits on Grand Cayman also suggest that they did not develop under present day climatic regime, but were probably developed in the past when the rainfall was much higher.

The various high stands of sea level in the past suggest that there were different established ground water circulation systems. As a result, the rocks were subjected to various diagenetic regimes and fluids in response to emergence and/or submergence. The complex distribution of the diagenetic fabrics in individual cavities is an excellent indication of the heterogeneity of the Bluff Formation which results in variations of ground water chemistry in close proximity.

## CONCLUSIONS

Integration of hydrogeological data, hydrochemical information and the geological evolution of Grand Cayman allows the following conclusions:

(1) ground water lens development is controlled by porosity and permeability distribution in the Bluff Formation,
(2) ground water chemistry is influenced by rain water recharge, evapotranspiration, and mixing effect.
(3) porosity creation processes include (i) leaching of aragonitic skeletal components, (ii) jointing, (iii) karsting, (iv) root boring, (v) microboring, and (vi) leaching of unstable zones in dolomite crystals,
(4) porosity destruction processes include (i) precipitation of carbonate cements and speleothemic calcite and (ii) deposition of internal sediments,
(5) the Bluff Formation has been subjected to numerous cycles of sea level changes since the deposition of the Cayman Member in Oligocene times,
(6) the rocks have been subjected to various diagenetic regimes in response to successive cycles of emergence and submergence, and
(7) the complex distribution of the diagenetic fabrics in the rocks is due to the variability of fluid chemistry in the joint and karst controlled aquifer.

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